Free-Piston Rankine Compression and Stirling Cycle Machines for Domestic Refrigeration

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Abstract

Free-piston compressors offer the opportunity for high efficiency, quiet, low cost and oil free vapor compression. Refrigeration compatibility is reduced to the consideration of the materials from which the compressor is built. The efficiency is improved on two levels, one being the reduction of friction and the other being the possibility of modulation by simply varying the drive voltage. In principle there is no difficulty in using hydrocarbon or other environmentally acceptable refrigerants. The part count is lower which should improve reliability. For applications involving domestic refrigeration and heat pumps, the free-piston Rankine system is the most efficient system known for capacities of above about 100W when electrical energy is used. The free-piston Stirling, on the other hand, is more efficient at lower temperatures and in smaller capacities. In addition, the Stirling is quiet, possibly of lower cost and uses completely benign working mediums (either helium or hydrogen). A variant of the free-piston Stirling, called the duplex, is able to use natural gas as its energy source. This configuration has the potential for the lowest operating cost (and highest indirect efficiency) of any cooling system.

Introduction

<u>Free-piston or linear machinery</u>

The basic difference between free-piston or linear machinery (as they are sometimes called) and conventional rotating machinery is that free-piston devices are driven by linear motors in a resonant fashion as opposed to being driven by a rotating motor and mechanical linkage. A number of advantages immediately accrue from the resonant linear drive, namely:

a) Side loads are vanishingly small which virtually eliminates friction and enables simple gas bearings to be used. Wear is therefore almost non-existent and oil is not required. In addition, since friction has been reduced to almost zero, the mechanical efficiency of the device is very high and internal heat generation very low.
b) The drive system is not rigid, thus internal collisions are not catastrophic.
c) Piston stroke is directly proportional to the drive voltage and is therefore easily controlled. This results in a simple, straightforward means to modulate the capacity and improve operating efficiency.
d) The number of moving parts is reduced which reduces cost and improves reliability.
e) Machining tolerances are reduced since alignment requirements are greatly ameliorated.

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f) The overall size and weight is reduced.
g) The linear motor is easily placed within the pressure vessel making it possible to hermetically seal the device and avoid leakage of the working fluid. This is, of course, also true for small conventional compressors.

Figures 1 and 3 show respectively (in schematic form) the configuration of the linear compressor and free-piston Stirling.

Free-piston compressor

Early efforts to build linear compressors generally floundered on trying to control the mean position of the piston. Some simple linear compressors (eg, Medo Inc.) do not control the piston mean position, but simply provide enough clearance so that the piston does not contact the head under any circumstances. In order to maximize the benefit of the free-piston arrangement, the piston mean position must be continually adjusted so that a minimum dead volume exists between the piston and head at all strokes. By so doing, the efficiency is considerably maximized. Methods to do this have been successfully implemented by Sunpower and are partly responsible for the high performance of these machines.

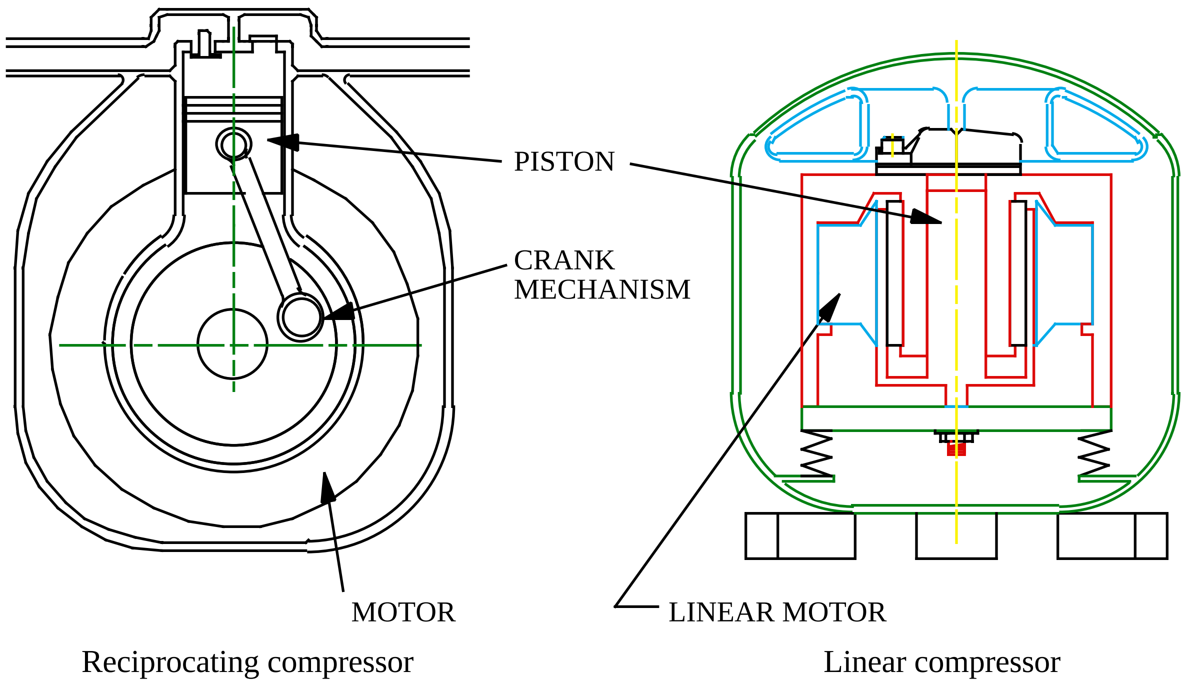

Figure 1 - Conventional reciprocating compressor compared to a linear compressor

Sunpower began investigating the linear compressor in 1991 under Environmental Protection Agency (EPA) sponsorship. A number of machines have been built and testing has been confirmed by independent laboratories. Overall, the performance has been between

15 and 23% better than typical high performance conventional machines. In addition to this, the elimination of oil lubrication allows the linear compressor to be compatible with a wide range of refrigerants. For example, some refrigerants tend to react with the lubricating oil while others are partially absorbed by the lubricating oils. Provided that the materials of construction are compatible, the choice of refrigerant is essentially unrestricted. Figure 2 shows the Sunpower prototype next to a conventional compressor of the same capacity.

Figure 2 - Prototype linear compressor (on right) compared to same capacity conventional compressor

Free-piston Stirling cooler

The Stirling cycle alternately compresses a fixed mass of gas (usually helium, but may be hydrogen or some mixture of gases) at one temperature level and expands it at another in a closed regenerative cycle in order to either lift heat or do work [1]. Originally Stirling machines were all driven kinematically, that is, by way of crank shafts and connecting rods as in most positive displacement machinery. The kinematic configurations have lead to a number of problems peculiar to the Stirling, these being the contamination of the internal heat exchangers by the lubricating oil, the difficulty in containment of the pressurized working gas and the high friction in the seals due to their more severe duty. In an effort to circumvent these problems, W. T. Beale suggested the free-piston configuration shown in Figure 3 [3].

A number of prototype machines have been built by research and development companies [1,2]. In particular, Sunpower has built three versions of a 250W capacity machine for General Electric and three versions of a 60W capacity machine (Figure 4) two of which were also tested by G.E. In addition, extensive analysis has been carried out to determine the relative performance of optimized free-piston Stirling coolers operating at domestic refrigeration temperatures. It would seem that the free-piston Stirling and a high efficiency compressor would have similar optimum performance at these temperatures. The compressor performance tends to improve over the Stirling as the temperature lift (difference between warm and cold temperatures) decreases, and, as the temperature lift increases, the Stirling rapidly gains ground over vapor compression. However, relative performance seems to be related to the capacity under consideration. Small, that is, low capacity free-piston Stirlings

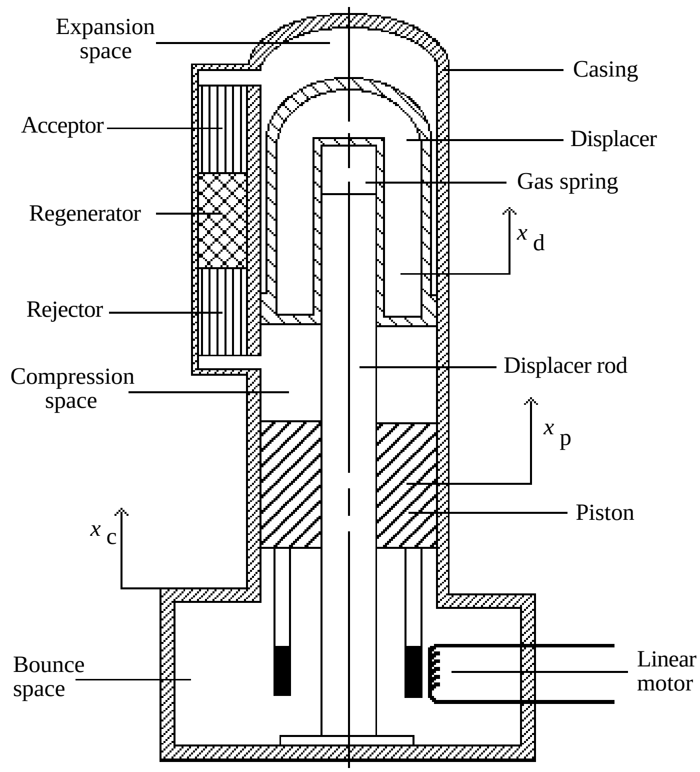

Figure 3 - Free-piston Stirling cooler

seem to retain performance better than Rankine systems do. A small refrigerator equipped with a Sunpower mini-cooler free-piston Stirling was tested by G.E. and found to consume 30% less input than current small compressor systems. Finally, since the motion of the moving parts are almost pure sinusoids, the higher harmonic content of the vibration is very small. This makes it easy to balance the machine with a simple dynamic absorber to levels of very low residual amplitude. A machine balanced in this manner is extremely quiet.

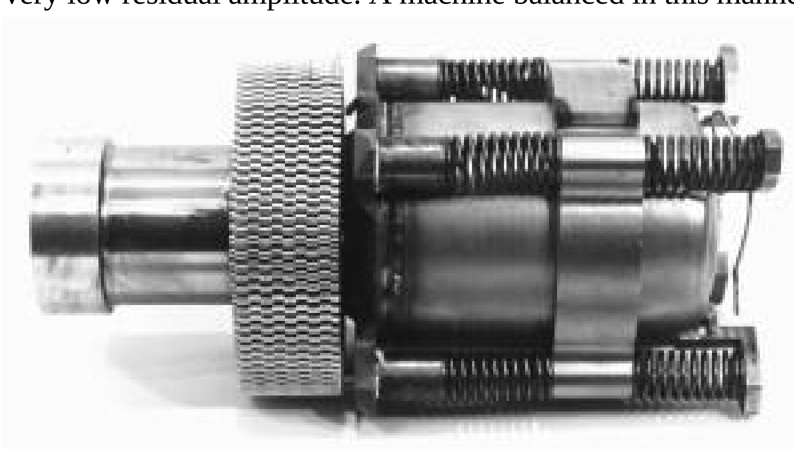

Figure 4 - Small free-piston Stirling cooler capable of cooling a 110 liter refrigerator

A proper evaluation of Stirling technology should include the duplex configuration. This machine, of which only a few prototypes have been built, consists of a free-piston Stirling engine driving a free-piston cooler by way of a common piston in a back-to-back configuration (Figure 5). The additional advantage over the basic free-piston configuration is that natural gas or other fuel source may be used to drive the cooler. Since the basic cycles are very efficient, the overall operating cost is predicted to be the lowest of all domestic cooling options [3]. In addition, the unit is compact and could be made to produce small amounts of electrical energy through a small alternator in order to power ancillary devices in the fridge. The user need see no apparent difference between a fridge so equipped and an electrically driven one. A duplex is much more efficient and much more compact than absorption devices which are the current machines of choice where heat energy is used as the input power. In fact, the overall energy usage efficiency for the duplex is high enough to be competitive in applications of low temperature lift, eg., domestic heat pumps [4].

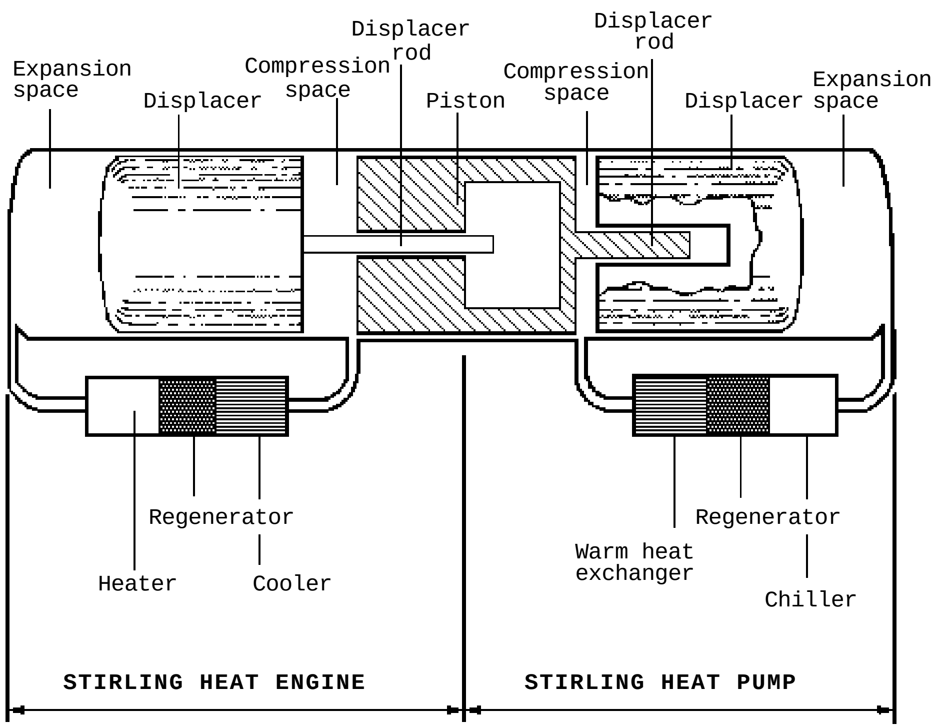

Figure 5 - (a) Schematic of Duplex Stirling. (b) Demonstrator

Performance

<u>Linear compressor</u>

The performance of a modulated 250W capacity linear compressor is shown in Figure 6. For comparison, fixed point standard compressors of various capacities are shown on the same graph. In every instance, the linear compressor is of superior performance. This clearly demonstrates the ability of the linear compressor to satisfy a wide range of capacities with one model. A smaller linear compressor of 115W capacity has also been developed and tested. At this time, only the ASHRAE performance point has been determined which showed a COP of 1.57, a full 23% better than a good conventional machine. Actually, this performance is very close to that achieved by the 250W unit when modulated to 115W lift. It is expected, however, that the smaller unit will maintain its performance better than the larger one when modulated to lower capacities. The entire domestic refrigeration requirements appear therefore likely to be satisfied by only two models, one a low capacity unit (say up to 120W) and the other a higher capacity unit (say up to 250W).

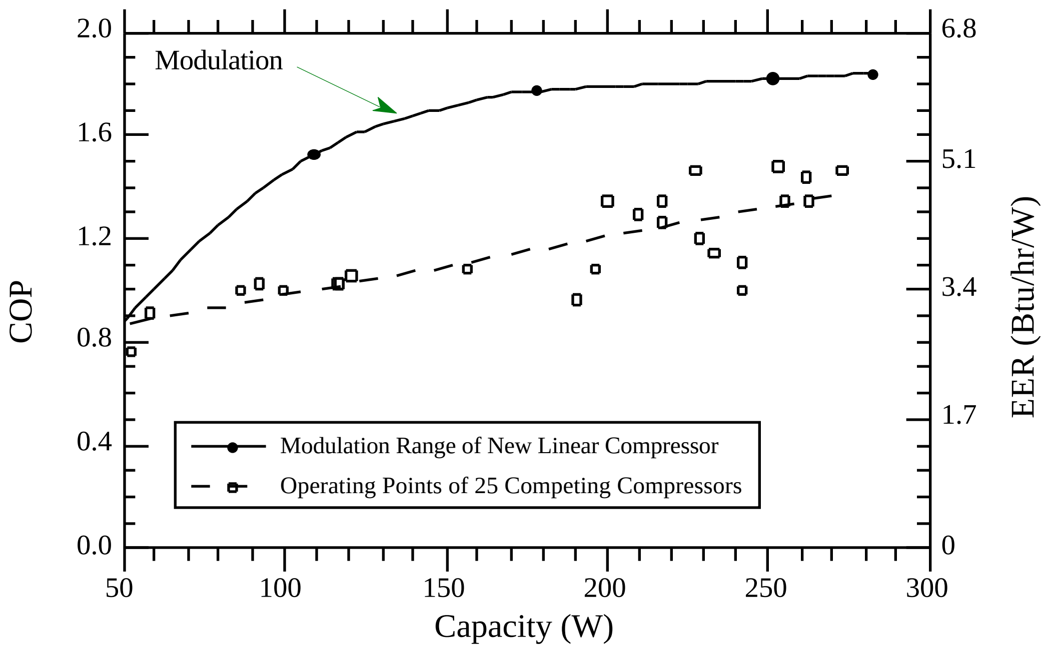

Figure 6 - Performance of modulating linear compressor compared to a number of fixed point conventional machines [7]. (COP ≠ heat lift / total input, both quantities in Watts)

Figure 7 shows the effect of modulation on performance. Normally, a higher capacity compressor will be set up with heat exchangers designed to accommodate the higher heat transfer. When the machine is modulated to lower capacities (for example, when the refrigerator door is closed for extended periods), then the heat exchangers develop smaller differential temperatures since they become more lightly loaded. This tends to improve the overall performance to higher levels than that predicted by simply operating at the standard ASHRAE set point rating condition. In addition to this, continuous modulation avoids the losses associated with re-establishing the thermodynamic cycle every time as is required in the conventional stop-start modulation. Modulation thus tends to have a multiplying effect on performance over and above the simple set-point advantage that the linear compressor demonstrates over conventional compressors.

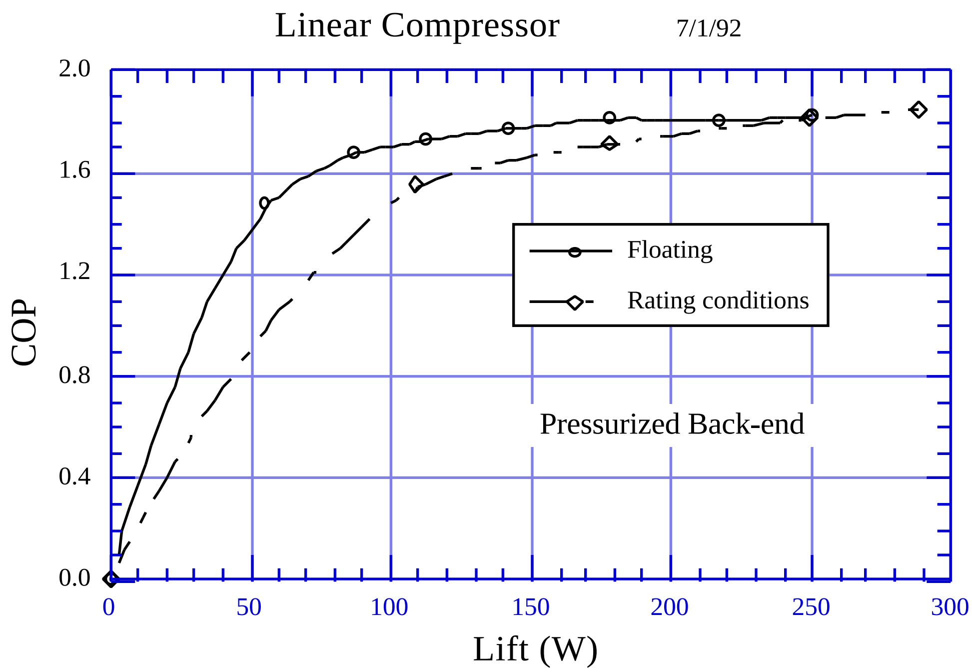

Figure 7 - Advantage of modulation on performance

Free-piston Stirling cooler

The Stirling units are not developed to the same level of performance as the linear compressor. So far, the best performance in the higher capacity units is about 32% of Carnot which translates to a COP of about 1.3. This is shown in Figure 8. All the same arguments concerning modulation apply equally to the Stirling. Theoretically, an optimized 200W capacity Stirling would be expected to have roughly the same performance as an efficient linear compressor system [5]. However, the Stirling appears to scale better to smaller sizes than does compressor systems. A number of *in situ* tests have been conducted at both G.E. and Sunpower on smaller units (60 to 110 liter refrigerators). These tests have shown that a small free-piston Stirling equipped fridge is at least 30% better in performance than current vapor compression units. Since then, a small hydrogen charged Stirling has been bench tested and found to be some 50% better in performance than the earlier helium charged prototype (Figure 9). It is expected that once tested in a small refrigerator, the hydrogen charged unit should show equivalent heat lift at better than 60% savings in input over the original equipment. The use of hydrogen is not seen as an impediment to safety. The gas inventory is small and pure hydrogen need not be used.

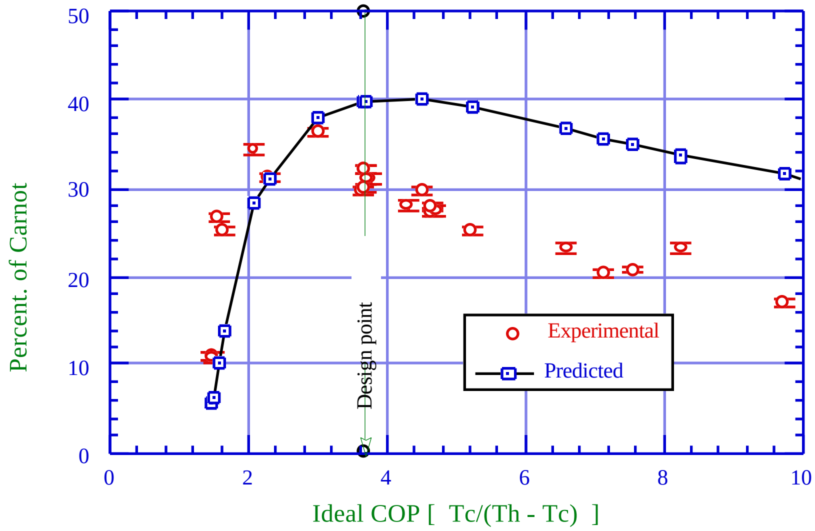

Figure 8 - Percentage of Carnot (or ideal performance) vs. Ideal COP for lifts between 200W and 257 W (includes motor losses)

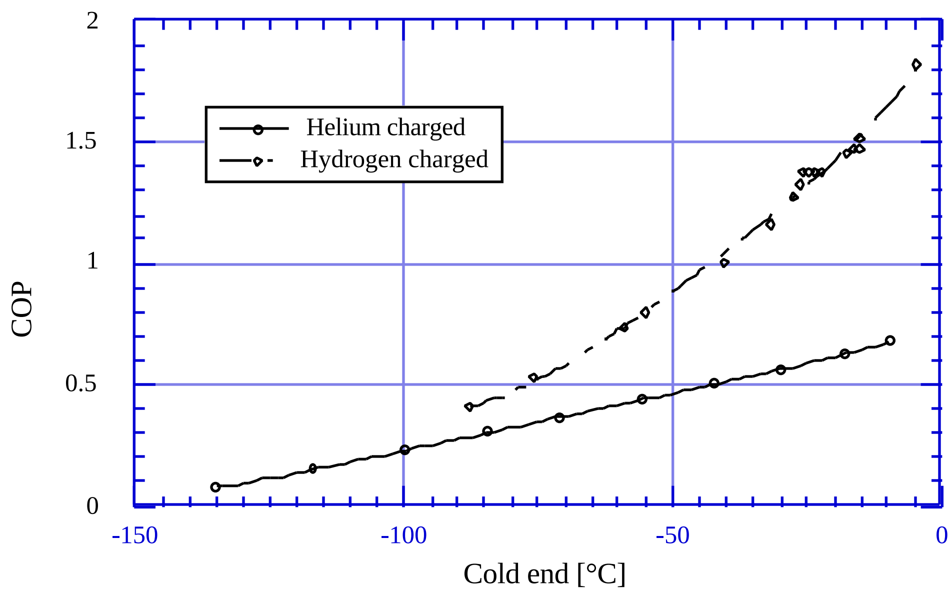

Figure 9 - Comparison between hydrogen and helium charged small Stirling coolers (includes motor losses)

Experimental performance of duplex machines is only available for a few technology demonstrator prototypes and is not really useful in determining the potential of this device. Instead, a study has been conducted where modest performance for the engine and cooler sections were assumed and, together with typical combustor efficiencies, an overall performance estimate has been calculated [3]. Figure 10 shows the results of this exercise and compares the estimated operating cost to that of a conventional compressor operating at identical conditions. Both systems are assumed to be running continuously and lifting 250W. Based on these numbers, the duplex refrigerator would have operating costs of between 61 and 46% less than the vapor compression system. Since this data was generated, likely improvements in compressors will reduce this advantage to between 46 and 24% which is still a very substantial savings. Continuous modulation is likely to give further advantage to the duplex since the on/off cycle losses associated with the vapor compression system is an additional burden.

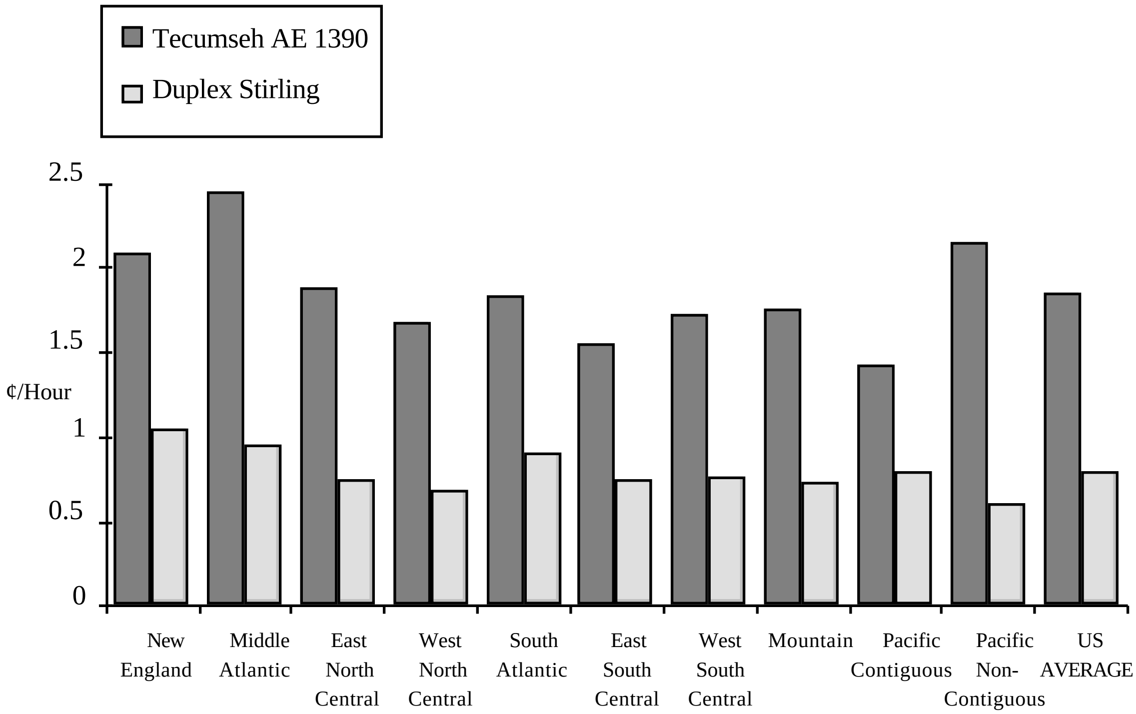

Figure 10. - Relative operating costs for the duplex [6]

Comparisons of the duplex to absorption cycle devices is also relevant since both systems use natural gas for primary energy. Based purely on energy usage, a thermally optimized absorption system [9] uses between 15 and 25% more energy than the duplex for the same duty. This comparison excludes modulation or likely improvements in the duplex.

Costs

Linear compressor

At this time a formal production cost estimate has not been completed. However, it is clear that the number of moving parts has been reduced as well as the number of close toleranced parts. Furthermore, the construction of the linear motor is much simpler than conventional motors and no expensive oils are required. Currently, permanent magnets are used in the linear motor. In principle, a wound field motor may be used but this would be of larger mass. Modulating the unit requires some electronics of differing complexity depending on the technique employed. Actually, it is possible to reduce the electronics to very simple sensing circuits not too different to that used in some refrigerators today. Given the foregoing, it would appear that linear compressors should be much cheaper than high performance, multiple speed crank-driven machines. How it stacks up against the new scroll compressors would depend to a large extent on the simpler components of the linear compressor and the fact that no oil is required.

Free-piston Stirling cooler

General Electric has done a formal costing of a 200W capacity refrigerator cooler [5]. Their numbers are very favorable towards the Stirling, being about $88/unit in quantities of 250,000 which is about twice the cost of current mass produced systems. With some cost reduction engineering and quantities of a million or more per year, the cost drops to only $30/unit which is very competitive. A further point is that the magnet assembly comes out at 24% of the total cost. With the continued fall in magnet prices plus the pressure of competitive bidding, the final production cost may even be lower. Investment and tooling costs were estimated at about $20 million. The smaller units have not been costed for this kind of production. However, it is likely that the cost advantage improves at the smaller sizes owing to the way the heat exchangers scale with respect to capacity. The duplex has also not been costed. But here again, the machine is basically very simple but needs a small high efficiency combustor. The motor size is greatly reduced and may even be eliminated if no electrical energy is required. Certainly, comparing the duplex to an absorption system, the duplex is much more compact and of less mass.

Summary

Linear machinery offer flexibility and performance advantages over conventional rotating crank systems. For the application considered here, namely domestic refrigeration, a strategy for optimum performance may be as follows:

a) Linear compressors for lifts above around 100W and where there is an overriding desire to use electricity.

b) Free-piston Stirling coolers for lifts below about 100W (exact cross over point has not been determined - may be as high as 200W). Higher capacities are competitive for lower temperatures (eg, deep-storage freezers). Again where electricity is used.

c) The duplex for all applications and lifts where operating cost is the most important criterion and natural gas is available.

Product costs definitely favors free-piston machinery over conventional machines for equivalent performance (where that can be achieved by conventional machines). Of the linear machines, product cost may favor the Stirling at the lower capacities. However, product costs may turn out to be similar so the overriding criterion may be operating cost savings which translate into performance.

Of these technologies, the linear compressor is the most developed followed by the small free-piston Stirling cooler. The duplex, which shows the most overall potential, is essentially undeveloped but proven in principle. Free-piston Stirling engines and coolers of appropriate sizes have been run, and individually have demonstrated that if combined would easily produce the performance estimated here.

Acknowledgements

The engineers responsible for the linear compressor work are R. Unger and N. van der Walt.

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